ENGINEERING CASE LIBRARY

ECL 229

THE ACHING AXLE (A)

A left rear axle was found in a field following a highway accident involving three vehicles. The role of the axle in the accident is pursued with special emphasis on design and fabrication; including functional requirements, material selection, fabrication, heat treating, and quality control.

THE ACHING AXLE

Part A

A tractor with a loaded semi-trailer (vehicle #1) was southbound in the right lane of a 4 lane highway, about 4:30 A.M., late in February, in southern Michigan. The night was clear but there was a light frost on the road surface. A small car headed north (vehicle #2) veered across the center of the highway and struck the dual wheels of the semi-trailer. This car continued northerly as it crossed back into the northbound lanes where it was struck by a second automobile (vehicle #3) which had been following the small car. A section of the police report of the accident is shown in Exhibit A1.

After daylight, it was observed that the left rear wheel and axle were missing from vehicle #2. After some searching, these were found in a nearby field and recovered. Photographs A-1 through A-5 show various views of the broken end of the axle. This fracture is close to the differential. Thus a short stub was left in the axle housing with most of the axle still attached to the brake drum.

Before trying to determine why this axle failed and presumably led to the three-vehicle accident, consider some general questions:

1. What are the functional requirements for an automobile axle? In other words, what are the service demands? What characteristics or properties must be developed in the axle to meet these demands?

2. What material should be selected for use in an automobile axle?

3. Having chosen the material, in what form (shape and/or condition) would you purchase it? How would you process it into the desired final shape or geometric configuration of the axle?

4. How would you process it (e.g., heat treatments) to develop the desired characteristics or properties to meet the functional requirements?

5. Having fabricated the axle so that it is ready to put into service, would you use some kind of quality control? If so, what?

Comments

This is an excellent opportunity to search in the library for information. Publications of such organizations as the Society of Automotive Engineers (SAE), the American National Standards Institute (ANSI), and the American Society for Testing Materials (ASTM) might be worth checking. There are various books about automobiles which might have information.

Publications of the SAE and the American Society for Metals (ASM), as well as variety of materials and materials processing textbooks, might be informative on many of the points raised by the indicated questions.

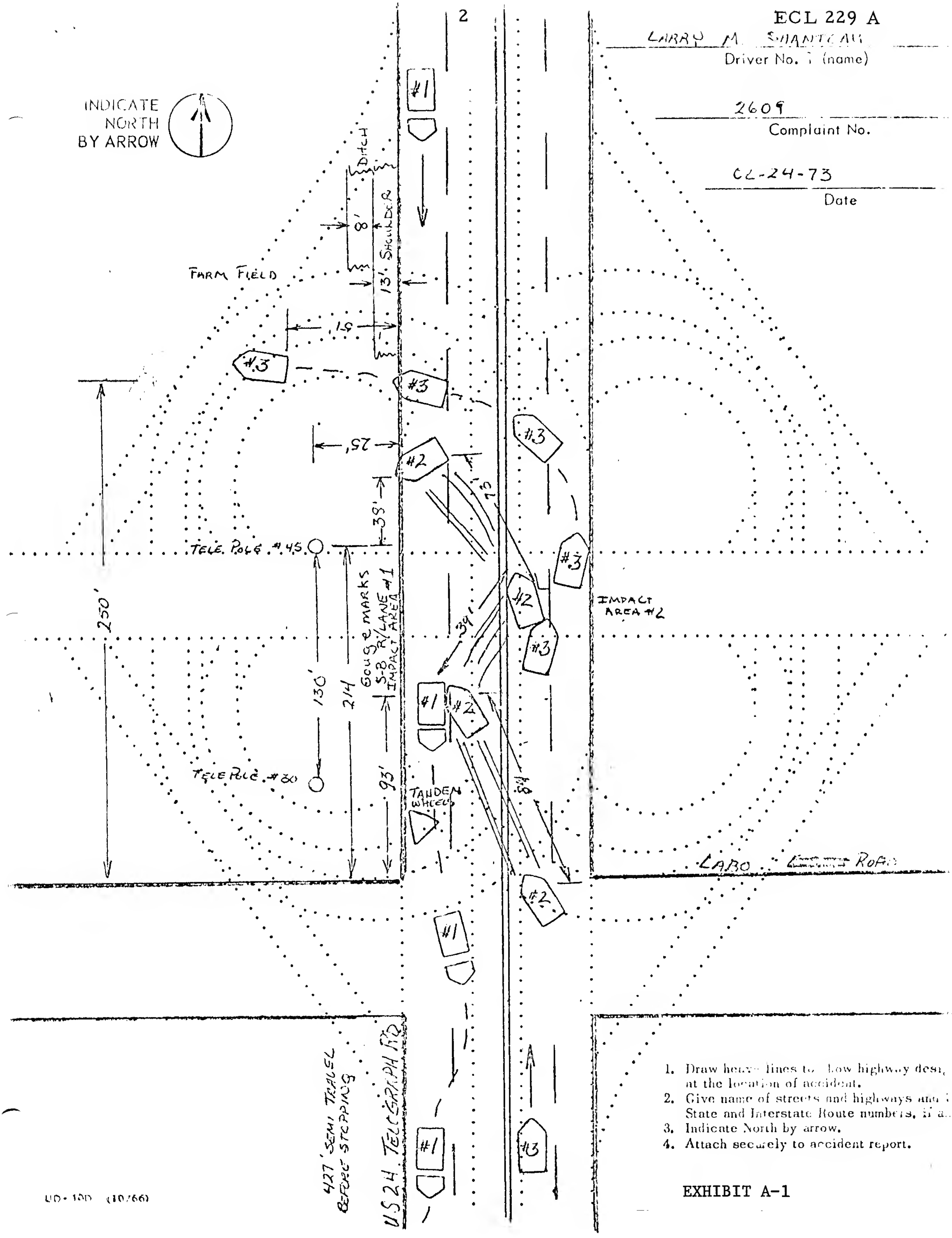
Although somewhat obvious, it may be worth noting that these five questions are not really separable despite being stated as if they were.

ECL 229 A

LARRY M. SHANTEAU
Driver No. 1 (name)

2609
Complaint No.

06-24-73
Date



1. Draw heavy lines to show highway design at the location of accident.
2. Give name of streets and highways and State and Interstate Route numbers, if any.
3. Indicate North by arrow.
4. Attach securely to accident report.

EXHIBIT A-1

UD-10D (10/66)

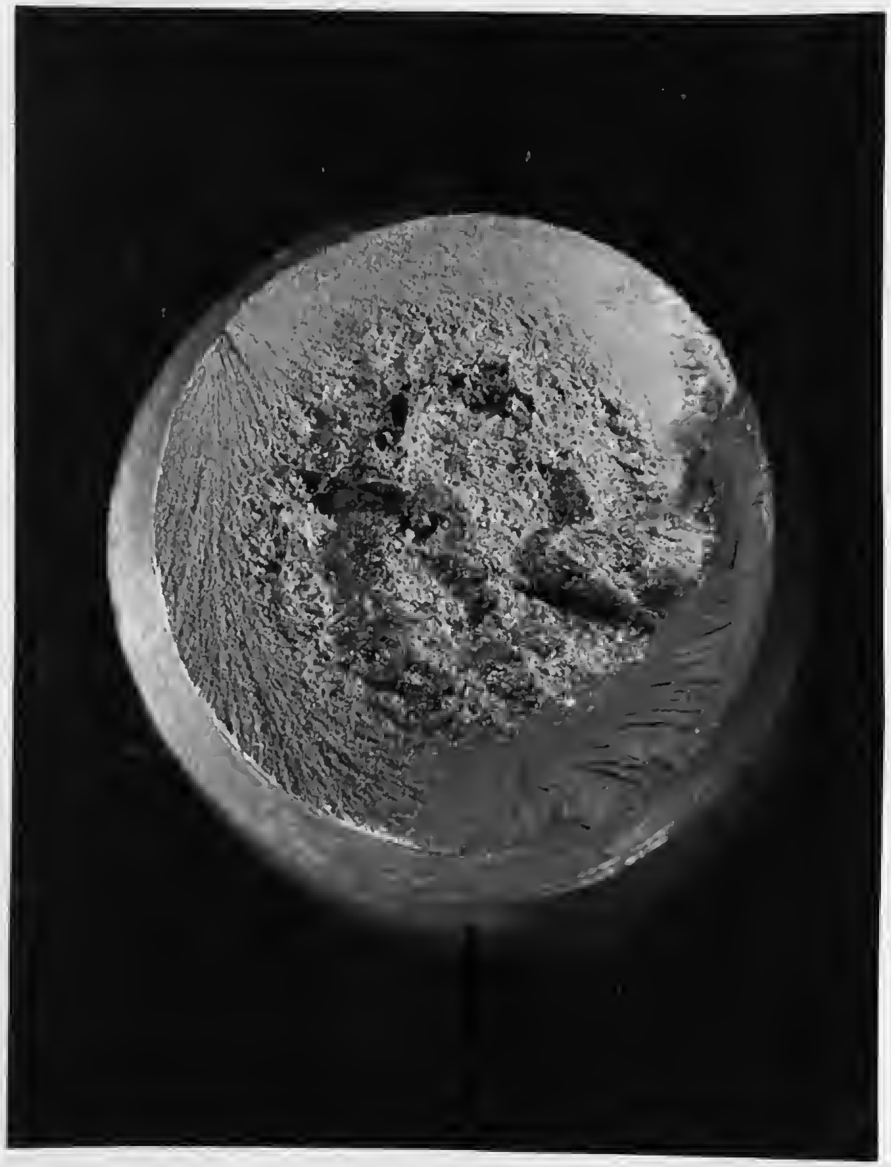


Photo A-1: Fracture surface as viewed along the axis of the axle. Approx. 3X

Photo A-2: Fracture surface as viewed along a line at about 45^{o} to the axis of the axle. Approx. 3X

Photo A-3: Fracture surface of axle as viewed perpendicular to the axis of the axle. Approx. 3X

Photo A-4: Fracture surface of axle as viewed perpendicular to the axis of the axle. Rotated 90° from the position in Photo A-3. Approx. 3X

Photo A-5: Junction of fracture surface and machined surface. Approx. 6X

THE ACHING AXLE

Part B

Consideration of Questions

1. Functional Requirements

Even if you spent some time looking for SAE Specifications with no success, it may still surprise you to know that the only related specifications of the SAE (1976 Handbook) are: "Axle and Manual Transmission Lubricants", Information Report SAE J308b; "Axle and Transmission Lubricant Viscosities", Recommended Practice SAE J306b; and "Trailer Axle Alignment", Recommended Practice SAE J875.

The ASTM has three specifications (A21, A383, and A729) in the 1976 listings, all of which relate to railway type axles. The first two of these are also ANSI Standards G57.11 and G57.12, respectively.

A request from the Executive Secretary of the Motor Vehicle Manufacturers Association in Detroit, Michigan for information drew the answer that the MVMA knew of no published specifications. Each manufacturer proceeds on the basis of in-house (proprietary) requirements or specifications.

A search of books yields somewhat better but still scanty information. Kuns [1]* says:

"Duties of the Rear Axle. Primarily, rear axles have been designed to carry the weight of the rear part of the car, but at the same time they serve as the means of driving or propelling the car along the highway. A third duty of the rear axle is carrying the brakes and acting as a transmitter of the braking effect if this is applied ahead of the rear axle. Many different designs have been worked out for serving these three major purposes. Housings, axle shafts, bearings, gears, propeller-shaft mountings, methods of taking the torque-reaction, brake arrangement and mounting, and methods of assembling may differ rather widely, but the three duties mentioned are the main ones which are met in service by all rear axles.

Axle Drive Shafts. The relative merits of the various types of rear axle design have long been matters of discussion for the engineers. These axle types are spoken of as plain live, semifloating, three-quarter floating, and full floating. This refers to the manner in which the driving strain and the load weight comes upon the axle shafts."

Heldt [2] has a chapter of about 40 pages on "Rear Axles" which discusses various configurations and gives some design formulae. The only statement relative to functional requirements is:

"Stresses in Axle Parts. A rear axle is subjected to both bending and torsional moments. The weight supported by it subjects it to bending moments and shear in the vertical direction, the axle acting as a single beam supported

*Numbers in brackets are items in the reference list.

at its ends and loaded at intermediate points. Driving and retarding (braking) forces on the wheel rims produce bending moments and shear in the horizontal fore-and-aft direction. Driving torque produces shear in the axle shafts and the axle housing; braking torque, in the housing alone, provided the brakes act directly on the wheels. In addition to these vertical and horizontal fore-and-aft forces, which are active as long as the vehicle is in motion (except for the braking forces), there are occasional transverse forces on the axle, as when the vehicle turns a corner (centrifugal force), when the wheel hits a road obstruction while skidding, or when the vehicle is being backed into a curb at an angle."

One SAE publication [3], a most valuable reference, says the following:

"Shafts and Axles. Shaft and axle loads are usually classified as torsional, bending or axial. These types of loading may or may not be present at the same instant, but if any two types of loading are present simultaneously, the principal stresses that occur are higher than those predicted from any individual loading. If two or more types of loading are present simultaneously, the combined effect can be found by using Mohr's circle to superimpose the effects of the individual loads.

In torsion, the critical torques are generally the starting and the shifting torques due to the inertia of the machine and/or the towed implements. Torque reversals also must be considered because they add to the stress range of the axle. Very often the maximum torque experienced is limited by the so-called clutch capacity of the wheels or the tracks. This is the maximum amount of torque that can be transmitted before the wheels or the tracks begin to slip, and it is not necessarily related to the torque that can be developed by the engine. Shafts may be subjected to momentary load surges caused by the machine striking obstructions with ground engaging equipment or running through excessive material, as in the case of balers and combines when windrow irregularities are met. Torsional vibration of rotating machinery is also a source of shaft loading and must be avoided either through the use of damping or through designing to keep the natural frequencies well below or above the operating speed.

Shafts must be designed to resist bending due to the inertia loading of the mass of the machine moving over a rough surface. Inertia loading can be critically important and should be carefully analyzed during the period of stress measurement. Inertia loading may be so high that the resulting stresses exceed the yield strength of the material. Bending failure may also occur in another plane, owing to forces set up while turning the machine. This is especially true of earthmoving equipment in which it is necessary to turn the machine in areas that are rocky and in which a portion of the machine may be blocked against some obstacle so that rotation of the machine can be accomplished only by moving this obstacle or by sliding the entire machine around it. Bending loads may also cause shaft vibration or whip. The wobble plate sickle drive on a combine or swather, the drive shaft of an automobile, or the power take-off drive on a corn picker are examples of parts that must be carefully designed to avoid vibration or whip.

Axial loads, although less prevalent that torsional or bending loads, can

also be troublesome. This situation frequently arises in power take-off drives to trailed equipment. In turning corners or traveling over uneven ground with field cutters, forage harvesters, and combines, the power take-off shaft is under relatively heavy torque and, at the same time, shaft extensions and contractions must occur. A similar situation occurs in automotive and truck driveshafts. The frictional forces in the splines during these operations are high, and hence axial adjustments are accompanied by high axial shaft forces. Thrust bearings and splines must be designed to withstand these loads. "

Fenton [4] has formulae for stress calculations but no indication of the functional requirements which necessitate the calculations.

After reading the above quotations, are the functional requirements fully stated? The answer is no since there are other factors which must also be considered. Obviously there is a combined stress problem since the axle must support bending, torsion, and axial forces. This implies a necessity for fatigue resistance. All of us who have hit curbs, bumps or holes in the road recognize a need for impact resistance as well.

There is a need for surface hardness for wear resistance, at least at the bearing interfaces and splines, and for greater strength on the surface to resist the applied loading. At the same time, even with a "hard" surface, the core must be relatively soft to resist impact and for energy absorption.*

In the axle, as in so many applications of materials, corrosion may be of concern. Most present-day automobile axles operate within some sort of axle housing. Some power shafts on various pieces of equipment, however, are "completely" exposed to the surrounding environment. Corrosion resistance can not be ignored. It must be considered, even though careful analysis may indicate that it is not important in the specific application.

There must be consideration of fabricability. In other words, how is the axle formed into its final dimensions from the original stock, as purchased. Related to this are questions of machinability and amenability to heat treatment.

There are questions about stability, i.e., will the axle, as manufactured and put into service, retain the composite of characteristics which have been developed in it? Presumably, as manufactured, the axle has "optimum" properties and any change caused by temperature, time, corrosion, etc., will be regarded as a degradation. This obviously is undesirable.

And last, but by no means least, is a question of cost. A few cents difference in total cost may not seem like much, but when multiplied by large numbers of pieces produced, this becomes a very appreciable consideration.

Perhaps you can add to the aspects which must be considered.

2. Material Selection

Material selection is a rather complex activity, as many factors have to

*See comment on pg B-11

be considered. In addition to the requirements implied by the functional requirements, one must consider a number of interacting factors, e.g., a lower strength material generally means more energy absorption (since lower strength generally means greater ductility) but this also implies a larger size for the same loading resistance. Low alloy steels have more strength and hardenability than plain carbon steels but are somewhat more expensive. There may also be questions of relative fabricability and machinability when comparing low-alloy and plain carbon steels. One may also question whether a steel must be used or whether some other material might not be at least as satisfactory.

It seems probable that any one of several different metals or alloys could be selected. Mantell [5] supplies one list as given in Exhibit B-1. A more recent listing is given by Metal Progress [6] in Exhibit B-2.

An interesting example of an axle shaft made from S7 tool steel for a racing car is given by the ASM [7] .

3. Fabrication

One would normally purchase the material in round bar form. In general, the round bar is roll forged to a blank with a flange formed on one by upsetting as indicated in Exhibit B-3. Full details on these processes can be found in several places [8, 9, 10] .

As indicated in Materials Engineering [11] .

"Precision forming by cold extrusion and warm forming will continue to replace forging, casting and, to a large extent, machining in the production of steel components such as drive pinions, Pitman shafts, gear blanks, yokes, wheel spindles and axle shafts, thereby markedly reducing materials, manufacturing and energy costs.

Savings in raw materials can be significant. Lower forming temperatures permit maintaining close tolerances at or near final part shape reducing the amount of starting stock. Lack of flash, gates, risers, kerf, etc., scrap "by-products" of casting, forging and machining, also reduces materials consumption. For example, the 8.5 lb(3.9 kg) of steel formerly required to produce a rear axle drive pinion by upset forging was reduced to 6.2 lb(2.8 kg) when the part was made by extrusion and warm forming. Additional cost savings were achieved in machining since there was less starting stock to remove to obtain the finished part.

Energy consumption also can be reduced. The reduction in process heat during cold and even warm forming of smaller blank (starting stock) sizes is significant compared to the energy consumed in hot forging or casting. It should be noted that warm forming also saves energy compared to cold forming when the latter requires interstage anneals between cold forming operations. In the drive pinion case, for example, gas-fired slot forging furnaces were replaced by induction-heated warm forming, saving 40,000 Btu/piece (42.2×10^6J/piece). Cold extrusion and warm forming also saves energy formerly consumed

in heat treatment since the process can provide controlled mechanical properties and microstructures. In the case of the pinion, another 4000 Btu/piece(4.2 x 10^6J/piece) are saved in post-forming anneals for microstructure. Overall, the drive pinion is now 30% less costly to produce."

After forming to approximately the final shape, rough machining would be performed as necessary. Such machining is visible in Figs. A-2, A-3, and A-4. Other rough machining would be performed at surfaces which will support bearings. This machining will leave some excess steel which is removed by grinding after heat treatment is completed.

4. Heat Treatment

Exhibit B-2 gives some indication of the heat treatment required for the alloys listed there. In general, one would heat treat to produce the desired structure (and properties) in the core. The harder case would normally be produced by induction heating of the surface followed by quenching and tempering [12]. Control of the depth of hardness is rather important. Boegehold [13], for example tells of an axle shaft which, after quenching and tempering, was Rockwell C56 on the surface and Rockwell C52 at the center. High tensile stress was developed at the surface. After a few cycles of repeated stress, it broke, almost explosively, into many fragments.

A further example of the necessity for control of depth is shown in Exhibit B-4. Bars such as A were from heats of steel that met specifications but contained chromium, nickel and molybdenum as residual alloying elements. Axle shafts made from these high-hardenability heats failed by shattering rather quickly. Axles made from type C failed quickly because of low hardenability. Axles made from type B, which produced a hardened shell approximately 3/16 inch thick (about 10% of the diameter), had a satisfactory life.

Details for heat treatment can be found in a number of textbooks and handbooks, particularly ASM publications [14, 15].

5. Quality Control

Each lot of steel should be checked to be sure it is the alloy specified. This can be done by spectrography for alloy content and by wet chemistry for carbon content.

Hardness tests are simple to perform. Hardness measurements on the surface will indicate if the specified hardness (and strength, by implication) has been developed in the processing. Depth of case and core hardness can be checked by randomly selecting axles, sectioning, and testing.

Ultrasonic testing can be used to examine for internal flaws such as chevrons (internal bursts and/or cup-cone fractures) in the forged axle. Ultrasonic testing can also be used to examine for burning (permanent damage such as incipient melting or intergranular oxidation from overheating).

Magnetic particle or dye-penetrant inspection can be used to examine for surface flaws which may lead to premature failure of an otherwise sound axle.

Details of these and other non-destructive test procedures can be found in various sources such as publications of the Society for Nondestructive Testing and Metals Handbook [16].

Testing of each axle, i.e., 100% inspection is expensive. It is common to use various sampling procedures.

Comment:

Fuchs [17] strongly disagrees with the statement that the core must be relatively soft to resist impact and for energy absorption. "It would be true if the axle were intended to be used like a bumper. But if the skin fails the axle is ruined, no matter how much energy the core can absorb. The difference in hardness between skin and core serves to set up rather high compression stresses in the skin, balanced by tension in the core. The compression strengthens the skin against fatigue as explained in reference 3, page 64 and pages 30 to 36. This is the key to the choice of axle materials in my opinion and in that of most others concerned with axle design. I feel that a discussion of this subject needs emphasis on the role of self stresses (residual stresses) to be useful."

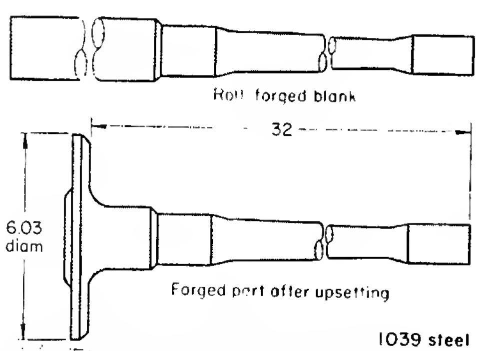
Fuchs also states there is a wide discrepancy between what we know and what we do. Even simple steady loading produces moving principal stress axes. Our theories are not capable of dealing with this situation. The combination of two different irregular loadings is also beyond our theories. The result is that we are left with reliance on experience and testing rather than on deductions. How to test is a serious question. Reference 3, pages 37-39, gives some insight into possible ways of approaching this including a full scale testing device in which tape recordings of actual field parameters are "played back" through a control system to produce the variable load input. There are variations on this scheme using random load generators, etc. The point, however, is that we still don't really know how to design an axle from "square one" without being dependent upon extensive testing and field experience to confirm a design.

Now that you are much better informed about axles, can you determine why the axle shown in Part A failed? If you do not have enough information, what additional data do you need? How would you obtain these data? What is your reaction to the opinion expressed by Dr. Fuchs?

Steels for Automotive Uses

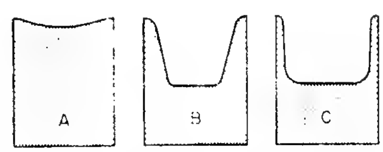
	Automobile, light truck, tractor						Heavy truck	Diesel engine
	Arms and knuckles		Axles and shafts		Universal joints	Sway eliminator bars	Crank-shafts	Crank-shafts
Tensile strength range, psi	125,000–165,000	150,000–200,000	150,000–200,000	175,000–225,000	125,000–175,000 (Core)	140,000–170,000	140,000–170,000	100,000 125,000
Mn	1340		1330	1340				
Ni-Cr	3130–35–40		3140–45					
Mo	4047–53		4063–68			4068		
Cr-Mo	4135–42		4140–45–50			4140	4142	
Ni-Cr-Mo		4337–40		4340–45	4317–20		4340	
Ni-Mo			4640		4617–20			
Cr						5145	5145	5046–5145
	8640–42		8640–50	8653				
Ni-Cr-Mo	8740–42		8740–50		8720			
		9840		9840–45				

Exhibit B-1



Axle shaft that was produced from a roll-forged blank in a 6-in. upsetter

Exhibit B-3



Variation in hardenability among different heats of 1¾-in. 1046 steel axle shafts quenched from 1550 F into 10% caustic soda to give surface hardness of 500 Bhn and core hardness of 300 Bhn.

Exhibit B-4

Exhibit B-2

Selection and Heat Treatment of Ferrous Alloys for Automotive Components

Cars	Axle Shafts	Output Shafts
A	1038 mod (0.70-1.00 Mn; cold extrusion, forged flange; induction hardened; surface Rc 45 min at 0.125, 0.025 in. after 365-385 F temper. Max depth of 95% martensite to be 0.200 in. 1050 mod (0.80-1.10 Mn; cold extrusion, forged flange, induction hardened & T; surface Rc 60 min, Rc 50 min at 0.120 in depth	1552 mod (1.35-1.65 Mn) forging, normalized & T to Bhn 197-229; induction hardened; surface, Rc 50-56
B	1039 cold extrusion; shaft induction hardened; surface hardness, Rc 45-55 Direct bearing type: 1050 mod cold extrusion; induction hardened, stress relieved; surface hardness Rc 60 min.	4027 forging, carburized, OQ & T; case depth 0.035-0.055 in 1042 forging; induction hardened, WQ & T at 300 F; case depth 0.090-0.155 in.
C	1038 cold extrusion; induction hardened and tempered at 450 F	1038 mod (0.40-0.60 Si) cold extrusion; induction hardened and stress relieved
D	1038 mod (0.70-1.00 Mn); hot flanged and cold extruded, induction hardened & T; surface hardness, Rc 50-58, Rc 45 min at 0.125 in. below surface	1141 bar stock; induction hardened and tempered; surface hardness, Rc 48 min
E	1038 mod (0.40-0.60 Si) cold extrusion; induction hardened, stress relieved, case depth 0.160 in min measured to Rc 35; surface hardness Rc 46-53 Direct bearing type: 1050 mod, cold extrusion; induction hardened, stress relieved. Surface hardness, Rc 60 min, case depth Rc 50 min to 0.125 in	1038 mod (0.80-1.10 Mn) cold extrusion; induction hardened and stress relieved
F	1038 forging; induction hardened, Rc 46-52 to depth of 0.120 in. min; Rc 28 max to 0.300 in. max	1052 mod forging, select very hardened
G	1050 forging; induction hardened to Rc 59 min.	1041 forging; OQ & T to Rc 28-34
Trucks A	1038 mod (0.40-0.60 Si) forging; induction hardened and stress relieved; case depth 0.160 in min measured to Rc 35; surface hardness, Rc 46-53	1038 mod (0.80-1.10 Mn) cold extrusion; induction hardened and stress relieved
B	1046 forging; WQ & T to Bhn 541-601; core, Bhn 250-350 41B50H or 50B50H forging; OQ & T to Bhn 285-321; induction hardened and tempered to Bhn 495-555 (the two suppliers use different practices)	8625 forging; carburized, OQ & T to Rc 58-63; case depth 0.040-0.050 in.
C	Rear: 1041 or 10B41 forging; induction hardened and tempered to Rc 52-59 Front: 15B37H; OQ & T to Bhn 255-302	EX 16, 17, or 54; carburized, marquenched & T to Rc 57-63, case depth 0.026-0.048 in.
D	4150 forging; through hardened to Bhn 388-444	8620 forging; carburized (… F), Q & T to Rc 58-63; case depth 0.040-0.050 in. 4315 forging; carburized (… 00 F), Q & T to Rc 58-63; case depth 0.040-0.050 in.
E	1041 forging; induction hardened to Rc 55 min	1132 forging; carbonitrided, OQ & T; case depth 0.010-0.020 in

Q, quenched; T, tempered; WQ, water quenched; OQ, oil quenched; AQ, air quenched.
A, B, C, designate a maker of cars and trucks. Steels refer to AISI-SAE standard grades.

Source: American Motors Corp., Kenosha, Wis.; Chrysler Corp., Detroit; Ford Motor Co., Dearborn, Mich.; General Motors Corp., Detroit; International Harvester Co., Ft. Wayne, Ind., White Motor Corp., Cleveland.

References

1. Kuns, R. G., "Automotive Essentials", Milwaukee, Wisconsin, Bruce Publishing Co., 1941

2. Heldt, P. M., "The Automotive Chassis", Philadelphia, Pa., Chilton Company, 3rd Edition, 1952

3. Graham, J. A., Editor, "Fatigue Design Handbook", Warrendale, Pa., Society of Automotive Engineers, 1968

4. Fenton, J., "Handbook of Automotive Design Analysis", London, England. Mercury House Business Publications, Ltd., 1973

5. Mantell, C. L. Editor, "Engineering Materials Handbook, New York, N. Y., McGraw-Hill, 1958, pg 4-33.

6. "Metal Progress Data book", Metals Park, Ohio, American Society for Metals, Mid-June 1976 pg 32, 34, 35.

7. Boyer, H. E., Editor, Metals Handbook, 8th Edition, Vol 10, "Failure Analysis and Prevention", Metals Park, Ohio, American Society for Metals, 1975, Ex 3, pg 66-67.

8. Jenson, J. E. Editor, "Forging Industry Handbook", Cleveland, Ohio, Forging Industry Association, 1966

9. Lyman, T., Editor, Metals Handbook, 8th Edition, Vol 5, "Forging and Casting", Metals Park, Ohio, American Society for Metals, 1970

10. Unterweiser, P. M., Editor, "Forging Design Handbook", Metals Park, Ohio, American Society for Metals, 1972

11. "Materials Engineering", Cleveland, Ohio, Vol 85, No. 2, February 1977, pg 18-19.

12. Wuerfel, R. K., "Characteristics of Hardened Axles", Metal Progress, December 1963

13. Boegehold, A. L., "Hardenability Control for Alloy Steel Parts", Metal Progress (ASM), Vol 53, May 1948, pg 697-709.

14. Lyman, T., Editor, Metals Handbook, 8th Edition, Vol 2, "Heat Treating, Cleaning and Finishing", Metals Park, Ohio, American Society for Metals, 1964

15. "Source Book on Heat Treating", Vols I & II, Metals Park, Ohio, American Society for Metals, 1975

16. Boyer, H. E. Editor, Metals Handbook, 8th Edition, Vol 11, "Nondestructive Inspection and Quality Control", Metals Park, Ohio, American Society for Metals, 1976

17. Fuchs, H. O., Design Division, Mechanical Engineering Department, Stanford University, Stanford, Calif., private communication, 6 September 1977

THE ACHING AXLE

Part C

Additional Observations of Failed Axle

The section of axle examined is about 2 feet long. The brake drum is attached at one end. The other end is a fracture surface.

Photograph A-1 shows the fracture surface as viewed directly along the axis of the axle. The lines in the periphery of the fracture surface clearly indicate the point of initiation of the fracture.

The general appearance of the fracture suggests the possibility of a fatigue fracture with a relatively smooth area in the vicinity of the point of initiation, a relatively rough region diametrically opposite, and a very rough central region. At the same time, however, the relatively smooth area is not as smooth as one normally finds in a failure which is clearly fatigue. This is not unusual in hard steels.

The rough machined surface of the axle in the vicinity of the fracture surface has a "pitch" between the "threads" of about 1/32 in.

It was observed that there is a "gouge" (or a gap of some sort) in the machined surface at the point of fracture initiation. This is shown in Photograph A-5. This gap is located in the crest of a "thread".

One section of the fracture end of the axle was removed by cutting along the plane indicated by the dashed lines in Photograph A-1 to a depth about 5/16 in. below the end of the machined surface. This was visually examined. A hardness traversed across a diameter was performed.

Polishing and macroetching indicate that the axle has been hardened on the surface to a depth of about 5/32 in. The microstructure appears to be reasonable. Hardness measurements (diamond pyramid with 1 kg. load) indicate that the surface hardness is in the order of Rockwell C 60 with a central core hardness of about Rockwell B 98. It should be noted, however, that in the position in which the hardness was measured (just below the machined area) there was a definitely lower hardness (about Rockwell C 50) directly at the surface (about 0.001 in. below) than at a greater distance below the surface.

Magnetic particle inspection of the fractured end of the axle gives no indication of any small cracks or other defects which can be detected by this test procedure.

Can you now determine what went wrong?

THE ACHING AXLE

PART D

Conclusions

1. The axle failed and thus "triggered" the sequence of events.

2. The axle failed because of overloading. The rough machining is, in itself, a source of stress concentration. The "gap" in the machined surface (Photograph A-5) increased the concentration. The lower hardness on the surface of the axle indicates decarburization of the steel. The combination of lower strength material on the surface and the stress concentration from the "notch" led to an effective overload.